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Sustainable Production of Open-End Rotor Yarn for Denim with Maximum Utilization of Recycled Cotton Sourced from Pre-consumer Hard Waste

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Article

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ABSTRACT

The textile industry is now focusing on sustainable approaches due to environmental concerns. The study explores an innovative approach to sustainable production utilizing recycled cotton sourced from hard waste. The article examines the characteristics of rotor yarns (recycled) manufactured from seven different percentages of recycled and virgin cotton, ranging from 0% to 100% recycled cotton. The study investigates the influence of cotton (recycled) percentage on yarn characteristics and results indicate when recycled cotton percentage in yarn increases, irregularity (CVm%), hairiness (H), and imperfections index (IPI/km) of yarns increase but strength and elongation% decrease. The study focuses on reducing the environmental issues of denim production by incorporating sustainable recycled cotton. Statistical analysis (Pearson correlation) confirms significant correlations (relationship) between recycled cotton proportion and yarn characteristics. The rotor yarns were tested in an air-jet weaving machine for denim production and found suitable for commercial production. The study gives significant insights into manufacturing sustainable yarns incorporating recycled fibres, focusing on environmental issues.

KEYWORDS

sustainable production, denim, recycled cotton, pre-consumer waste, rotor yarn, yarn characteristics

INTRODUCTION

In recent times environmental consciousness has become a global concern and the textile industry is trying to shift toward sustainable practices. The requirement for eco-friendly techniques has led to novel approaches in production systems, with a specific focus on minimizing waste and reducing environmental impact. One remarkable advancement in this concern is the development of sustainable recycled yarn, a hopeful solution that directs both economic and ecological disputes related to conventional textile manufacturing.

The production of fibres in 2021 is about 113 million tons and is assumed to be 149 million tons in 2030 and cotton will be the 2nd most important fibre in 2021 with nearly 24.7 million tons in volume [1]. To cultivate cotton seeds, many natural resources like water and others are consumed [2]. In addition, recently waste generation has notably increased in manufacturing (textile) industries [3,4]. Industries (textile) produce waste of nearly 92 million tons globally, which is assumed to be nearly 134 million tons by 2030 annually [5]. In addition, the industry (textile) also utilizes limited resources such as freshwater, raw materials, energy, and land while using hazardous substances that contaminate natural resources like water [6].

Moreover, the manufacturing company produces nearly 20% of wastewater globally and approximately 10% of entire carbon emissions [7]. Textile factory is the dominating sector that generates waste remarkably [8]. Wastes (textiles) can be grouped into three segments: pre-consumer, post-manufacturing, and post-consumer wastes [9,10]. During production, the generated waste is called pre-consumer waste such as short fibres, yarns (rejected), fabrics (cutting parts), and others [11]. In general, people throw their used and old garments into the environment which causes the majority of waste (textile) generation to be post-consumer waste [12-14]. The most difficult work is to recycle the waste (post-consumer) within the industry [15]. To think about these realities, there are some remarkable approaches toward sustainable ways to lessen the production of fibre [16]. For this circumstance, using recycled cotton extracted from hard waste can be a perfect substitute for cotton production.

Utebay discussed the influence of recycled cotton quantity on final yarn quality where recycled cotton and 100% virgin cotton were blended at the fibre stage and fed to the blowroom [17]. Okandan examined the influence of spinning specifications (OE-rotor) on yarn properties manufactured from recycled cotton and virgin cotton mixture (50:50) where cotton (recycled) and cotton (virgin) were blended at the fibre stage and fed to the blowroom [18].

Ute et al. explored the use of spinning waste generated at various stages of yarn production mixed with fabric waste and 100% cotton (virgin) for a sustainable approach [19]. Awgichew et al. investigated the influence of recycled fibre yarns (rotor) for the manufacturing of fabrics (handloom) where cotton (recycled) and cotton (virgin) were blended in a mini carding machine [20]. Islam et al. investigated the comparative analysis of yarn (rotor) utilizing waste (cutting) where cotton (recycled) and cotton (virgin) were blended by hand mixing and fed to the blow room [21]. Arafat and Uddin discussed the production of recycled yarns (ring) using waste (post-consumer and pre-consumer) where cotton (virgin) and cotton (recycled) were blended in the fibre stage and fed to the blowroom [22].

Telli and Babaarslan investigated the yarn characteristics made from polyester and cotton (recycled) extracted from yarn waste [23]. Yilmaz et al. compared the influence of various cotton wastes on several yarns (rotor) types where cotton (recycled) and cotton (virgin) were blended in the fibre stage [24]. Şentürk and Üte investigated the characteristics of fabrics (knitted) manufactured with yarns (ring and rotor) having cotton fibre (recycled) where fibres were blended in the fibre stage and fed to the blowroom [25]. Yuksekkaya et al. compared the characteristics (physical) of fabric and yarn (rotor) made with virgin cotton and recycled cotton where fibres (recycled and virgin) were blended in the fibre stage and fed to blowroom [26]. Duru and Babaarslan discussed the effect of roller speed on yarn (rotor) quality where yarn was manufactured from polyester and cotton (extracted from wastes) [27]. Khan et al. examined the characteristics of yarn (rotor) from soft waste where blending of fibres (soft waste & virgin cotton) was blended in blowroom stage [28]. Telli and Babaarslan investigated the blended yarn and fabric (denim) properties where cotton fibres were sourced from postindustrial denim fabric waste and polyester fibre was extracted from consumer waste [29]. Arafa investigated the rotor yarn characteristics with various counts produced from several percentages of waste and found variation in results [30]. Halimi et al. discussed the influence of wastes (cotton) and several specifications of spinning on the quality of rotor yarns [31]. Uddin and Roy investigated the yarn (mélange) properties produced from fibre (recycled) where several spinning techniques were used [32].

Although some studies investigate the properties of yarns produced from several fibres where fibres (recycled and virgin) were blended in different stages of yarn production (rotor), no works have been found where fibres (recycled and virgin) were blended in the draw frame of rotor yarn manufacturing. Based on the above literature it has been found that the quality of rotor yarns is not so good in the case of characteristics when fibre blending has been performed in the blowroom stage. The article focuses on producing yarns (rotor) using cotton fibre (recycled and virgin) blended in the drawing stage investigating yarn properties and finding the deviation of yarn characteristics which was produced by blending recycled cotton and virgin cotton in the blowroom stage. Moreover, the article also investigates the influence of fibre length and short fibre contents blending with 100% cotton on rotor yarn quality.

EXPERIMENTAL

Materials and Methods

Materials

In the work to produce Ne 8.25/1 yarn with homogeneous yarn quality appropriate for denim production, commercial-scale modern machines with continuous operation were used. Two different fibres such as 100% cotton (virgin) and cotton (recycled) used to manufacture yarn are indicated in Figure 1. 100% cotton (virgin) fibres were collected (purchased) from local suppliers and pre-consumer hard wastes (100% cotton) were collected from the ring section, winding section, and rope warping section and then shredded by a shredding machine to produce fibre (recycled).

a) b)

Figure 1. Materials utilized in the study: (a) Recycled cotton, (b) Virgin cotton

The quality of recycled cotton and virgin cotton fibre are exhibited in Table 1 which were tested by the Uster HVI Spectrum. Fifteen test results were performed and evaluated mean values were taken for analysis. Here seven yarns with several percentages of cotton (virgin) and recycled cotton were produced with a rotor frame.

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Table 1. Characteristics of recycled and virgin cotton fibres

Fibres	SCI	Micronaire (µg/inch)	Maturity	Length (mm)	UI (%)	SFI	Strength cN/tex	Elongation (%)	Moisture (%)	Trash content%
Recycled cotton	80	4.30	0.87	26.43	75.35	17.50	26.57	5.69	6.91	2.50
100% virgin cotton	141	4.52	0.90	29.47	84.72	6.75	31.49	6.65	7.48	137.20

Methods

The hard wastes collected from the ring, winding, and rope warping sections were shredded by a shredding machine (Mechanical recycling opener) to produce fibre (recycled). The shredding machine consists of four opening positions. The parameters (production) of the shredding machine are expressed in Table 2.

Table 2. Production parameter shredding machine

Production parameter	Machine setting
Brand name	OMMI MECHANICAL RECYCLINGOPENER
1st group rough opener garnished cylinder speed (m/min)	15
1st group rough opener needle roller speed (m/min)	2800
1st group condenser speed (m/min)	4.5
2nd group rough opener garnished cylinder speed (m/min)	15
2nd group rough opener needle roller speed (m/min)	2800
2nd group condenser speed (m/min)	5
3rd group rough opener garnished cylinder speed (m/min)	18
3rd group rough opener needle roller speed (m/min)	2900
3rd group condenser speed (m/min)	5.5
4th group rough opener garnished cylinder speed (m/min)	18
4th group rough opener needle roller speed (m/min)	2800
4th group condenser speed (m/min)	18

The cotton (recycled) and cotton (virgin) were fed separately to the blowroom and then to the carding machine to produce two different Ne 0.08 count card slivers (recycled and virgin cotton). The unevenness (CVm%) of recycled cotton card slivers is 4.39% and the unevenness (CVm%) of cotton(virgin) card slivers is 3.59%. The parameters (production) of the blowroom and carding are expressed in Table 3 and Table 4 respectively.

Then six carded slivers were fed to the 1st draw frame with recycled cotton card sliver number, and the virgin cotton card sliver number ratios were as follows 0:6 (0% recycled cotton + 100% virgin cotton), 1:5 (17% recycled cotton + 83% virgin cotton), 2:4 (33% recycled cotton + 67% virgin cotton), 3:3 (50% recycled cotton + 50% virgin cotton), 4:2 (67% recycled cotton + 33% virgin cotton), 5:1 (83% recycled cotton + 17% virgin cotton) and 6:0 (100% recycled cotton + 0 % virgin cotton).

Then the produced 1st drawn slivers containing a blend of virgin and recycled cotton with various percentages were fed to the 2nd draw frame separately with a required number to produce seven different 2nd drawn slivers. The production parameters of 1st and 2nd draw frames are shown in Table 5. The unevenness and CVm% of seven different 2nd drawn slivers are shown in Table 6. The AFIS report of Cotton (recycled) and cotton (virgin) and 2nd drawn sliver are expressed in Table 7. For the AFIS test mass technique has been used.

Table 3. Production parameter of blow room

Machine name	Production parameter	Value
Coarse cleaning machine	Brand name	MARZOLI EXENEL OPENER
	Beater-1 speed (RPM)	670
	Beater-2 speed (RPM)	800
Mixing machine	Brand name	MARZOLI MIXER
	Beater speed (RPM)	75
Fine cleaning machine	Brand name	MARZOLI FINE OPENER
	Beater-1 speed (RPM)	780
	Beater-2 speed (RPM)	1200
	Beater-3 speed (RPM)	1770

Table 4. Production parameter of carding

Production parameter	100% virgin cotton	Recycled cotton
Brand name	MARZOLI CARDING MACHINE	MARZOLI CARDING MACHINE
Production (kg/h)	60	40
Production speed (m/min)	137	93
Licker-in speed (RPM)	870	870
Cylinder speed (RPM)	500	500
Flat bar speed (mm/min)	325	325
Sliver count (Ne)	0.08	0.08
Doffer speed (m/min)	114	77
Calender roller speed (m/min)	148	100
Coiler Speed (m/min)	135	91

Finally, the seven different 2nd drawn slivers were separately fed to the machine (rotor) to manufacture seven different yarns, and characteristics of yarn including strength and elongation%, imperfection index/km, hairiness (H), and their variation(sh), and unevenness% were examined. For comparison, rotor yarns (Y1) produced with 100% cotton (indicated by 0%/100%) are incorporated. The parameters of production (spinning) of the open-end (OE) rotor spinning to produce yarn (recycled) have been shown in Table 8.

Table 5. The production parameters of 1st and 2nd draw frames

Production parameter	1st draw frame	2nd draw frame
Brand name	MARZOLI 1st DRAWING MACHINE	MARZOLI 2nd DRAWING MACHINE
Feed sliver count (Ne)	0.080	0.1
Delivery sliver count (Ne)	0.10	0.1
Number of doublings	6	7
Production speed (m/min)	850	650
Roller pressures (bar)	6	6
Drafting Zone setting (mm)	Distance from front roller to middle roller: 39mm; distance from back roller to middle roller: 41mm	Distance from front roller to middle roller: 39mm; distance from back roller to middle roller: 41mm
Total draft	7.45	6.6
Break draft	1.6	1.7

Table 6. Characteristics of 2nd drawn slivers

Samples	Compositions	CVm%
1	0% recycled cotton+ 100% virgin cotton	4
2	17% recycled cotton+ 83% virgin cotton	4.11
3	33% recycled cotton+ 67% virgin cotton	4.15
4	50% recycled cotton+ 50% virgin cotton	4.49
5	67% recycled cotton+ 33% virgin cotton	4.95
6	83% recycled cotton+ 17% virgin cotton	5.40
7	100% recycled cotton+ 0% virgin cotton	6.01

Fifteen tests were performed and evaluated mean values were taken for analysis. The morphology of manufactured yarns has been examined by an optical microscope to show the hairiness variation of the produced yarn. In addition, the performance of several yarns has been tested by utilizing a weft yarn in an air-jet weaving machine (Picanol Ommi Summum) to produce fabric (denim) and the construction of fabric was 3/1 'Z' twill with EPIxPPI (40x36).

The CVm% (coefficient of mass variation), imperfection index (thin place (-40%), neps (+200%), and thick place (+50%)/km), hairiness (H), and their variation(sh) were examined by Uster® Tester 4 (UT 4, Uster Technology, Switzerland) maintaining the standard TS 247 EN ISO 2060, DIN 53830 and ISO 16549, ASTM 1423. The test length was 100 m and the cut length was 1 cm for Uster® Tester 4. The elongation% and strength (RKM, B-work) characteristics of yarns were tested by Uster Tensorapid-3 following the standard ISO 2062, DIN 53 834, ASTM D-1578, JIS. The test length was 50 cm and the testing speed was 500cm/minute for Uster Tensorapid-3. Additionally, Statistical analysis (Pearson correlation) was applied to investigate the relation between recycled fibre% and yarn characteristics.

Table 7. The AFIS report of Cotton (recycled), cotton (virgin), and 2nd drawn sliver

Materials	Cotton (virgin): Cotton (recycled)	Fibre neps size (µm)	Fibre neps/g	Seed-coat neps size (µm)	Seed-coat neps/g	Short fibre contents (w) % (< 12.7 mm)	Upper Quartile length (mm)	Fineness (mtex)
Cotton (virgin) fibre (in bale)	100:0	670	199	1099	6	6.7	26	154
Cotton (recycled) fibre (in bale)	0:100	830	86	1301	60	17.9	25.91	158
2nd drawn sliver	100:0	602	120	603	1	7.1	25.86	154
	83:17	607	154	699	2	7.9	25.71	155
	67:33	614	188	735	2	8.3	25.5	155
	50:50	621	210	760	3	8.8	25.30	156
	33:67	626	240	788	3	9.1	25.16	156
	17:83	630	280	801	4	9.7	24.9	157
	0:100	633	830	821	4	10.2	24.71	157

RESULT AND DISCUSSION

Morphology of yarns

Here, the morphology of manufactured yarns has been investigated by an optical microscope to examine the hairiness of different yarns only. Figure 2 expresses the microscopic images of several yarns (Ne 8.25) with various percentages of virgin cotton / recycled cotton and it is clear that the yarn's hairiness increases gradually when the recycled fibre percentage increases because the fibres (recycled) hold huge short fibre and the length of fibre is comparatively low that has been indicated in Table 1.

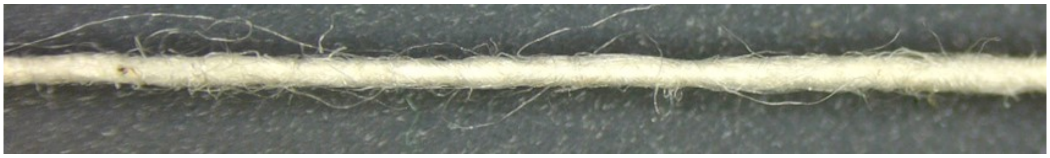
Table 8. Spinning (production) parameters of Ne 8.25/1 rotor yarn

Production parameter	Rotor spinning (OE) setting
Rotor type	TT_640_B (Diameter: 40 mm)
Rotor speed	90000 rpm
Opening roller speed	8500 rpm
Opening roller type	B_174_DN
Twist	485.6 tpm
Twist co-efficient (α)	4.3
Yarn delivery speed	185.3 m/min
Drawn sliver count	Ne 0.10

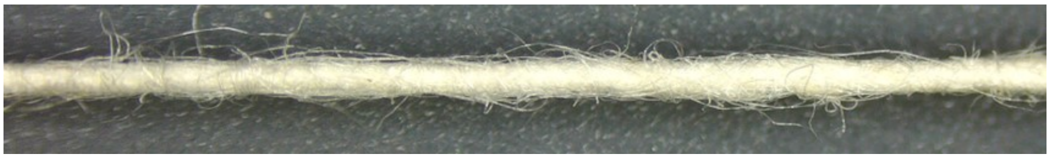
Properties of yarns

CVm% of yarn

The CVm% (co-efficient of mass variations) of yarn is generally utilized to show the unevenness % or irregularity. The CVm% of Ne 8.25 yarns manufactured with various percentages of cotton (recycled) / cotton (virgin) through rotor machine are illustrated in Figure 3. Moreover, for making the comparison, the CVm% of yarn (rotor) made with virgin cotton (indicated by 0%/100%) is incorporated. It is noticeable that the CVm% of every yarn having fibres (recycled) is more than yarn manufactured from 100% cotton (virgin). Additionally, CVm% of yarn shows higher values continuously when the recycled fibre percentage increases because the fibres (recycled) contain remarkable amounts of short fibre and the length of fibre is relatively low which has been indicated in Table 1. In several steps of the drafting process, the short fibres cannot be controlled during drafting actions in several processes of spinning techniques which causes irregular wave formation in the drafting action contributing to higher unevenness of yarn. It is also noticed that CVm% of yarn is increased by 3.74% from 0% recycled cotton + 100% virgin cotton (Y-1) yarn to 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn and 10.9% from 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn to 100% recycled cotton + 0% virgin cotton (Y-7) yarn. The CVm% of yarn is increased continuously from Y-1 to Y-7 yarn because of having an increased amount of short fibre percentage.



a)



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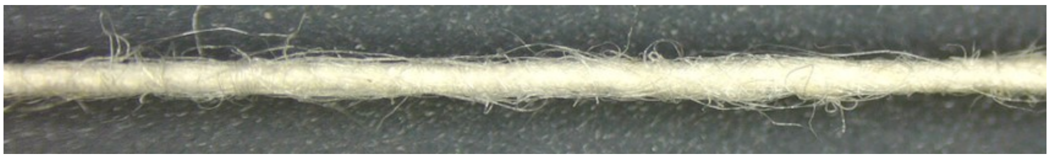

c)

d)

e)

f)

g)

Figure 2. The microscopic image of manufactured yarns a) Y-1: (0% recycled cotton + 100% virgin cotton), b) Y-2: (17% recycled cotton + 83% virgin cotton), c) Y-3: (33% recycled cotton +67% virgin cotton), d) Y-4: (50% recycled cotton + 50% virgin cotton), e) Y-5: (67% recycled cotton +33% virgin cotton), f) Y-6: (83% recycled cotton + 17% virgin cotton), g) Y-7: (100% recycled cotton + 0% virgin cotton)

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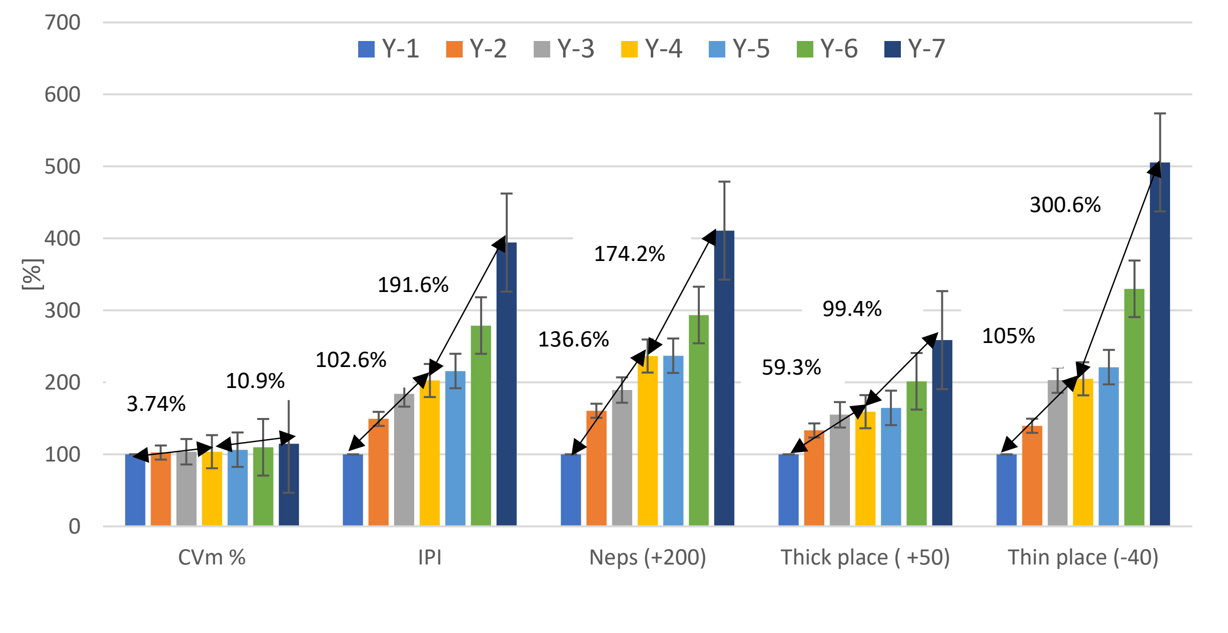
It has been indicated in the previous work that the CVm% of yarn (Ne 8/1) is 15.3% which was produced by rotor spinning utilizing 50% recycled cotton and 50% virgin cotton where blending of fibre was done in the blowroom stage [30]. In this study, the CVm% of yarn (Ne 8.25/1) is 13.33% for 50% cotton (recycled) and 50% cotton (virgin) blend yarn. So, it is clear that when blending is done in 1st draw frame stage the CVm% has been reduced.

Imperfection index (IPI) of yarn

While examining the yarn’s unevenness, the IPI of yarns is also considered. The thick place (+50), thin place (-50), and neps (+200)/km are generally examined to calculate the IPI of yarns. The thin place (-50)/km values for this work in the manufactured yarns were nearly zero, so the thin place (-40%)/km is considered for IPI computation. Yarn’s imperfections have a remarkable effect on various processes such as weaving, sizing, warping, and the visual fabric’s appearance. The imperfection index including the thin place (-40%/km), neps (+200%/km), and thick place (+50%/km) of yarns is indicated in Figure 3. It is noticed that when recycled fibre in yarn increases, the IPI also increases because recycled fibres contain significant amounts of short fibre, and the length of fibre is comparatively low. It is also noticed that the IPI of yarn is increased by 102.6% from 0% recycled cotton + 100% virgin cotton (Y-1) yarn to 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn and 191.6% from 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn to 100% recycled cotton + 0% virgin cotton (Y-7) yarn. The IPI of yarn is increased continuously from Y-1 to Y-7 yarn because of having an increased amount of short fibre percentage. It has been indicated in the previous work that the IPI of yarn (Ne 8/1) is 594 which was produced by rotor spinning utilizing 50% recycled cotton and 50% virgin cotton where blending of fibre was done in the blowroom stage [30]. In this study, the IPI of yarn (Ne 8.25/1) is 395.35 for 50% cotton (recycled) and 50% cotton (virgin) blend yarn. So, it is clear that when blending is done in 1st draw frame stage the IPI has been reduced.

Yarn hairiness and its variations

The hairiness of yarns and their variation are also considered significant quality parameters among several properties. The number of hairy ends that are visible on the surfaces of the yarns is used to determine the hairiness level [33]. A remarkable quantity of hairiness may affect negatively in visual characteristics of products [34]. Hairiness variation may affect the texture and visual appeal by diminishing the quality of finished products [35]. Figure 4 illustrates the yarn's hairiness (H) and their variations (standard deviation of hairiness, sh) and it is noticed that both values of all yarns having fibres (recycled) are higher than yarns manufactured from 100% cotton (virgin). In addition, hairiness (H) and its variation (sh) of yarns show higher values gradually when the recycled fibre percentage increases because the recycled fibre contains huge short fibres and the length of fibre is relatively low as was previously explained. During yarn production, the short fibres remaining in the fibre (recycled) cannot be controlled leading to higher hairiness of yarn. It is also seen that the hairiness of yarn is increased by 2.99% from 0% recycled cotton + 100% virgin cotton (Y-1) yarn to 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn and 15.72% from 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn to 100% recycled cotton + 0% virgin cotton (Y-7) yarn.

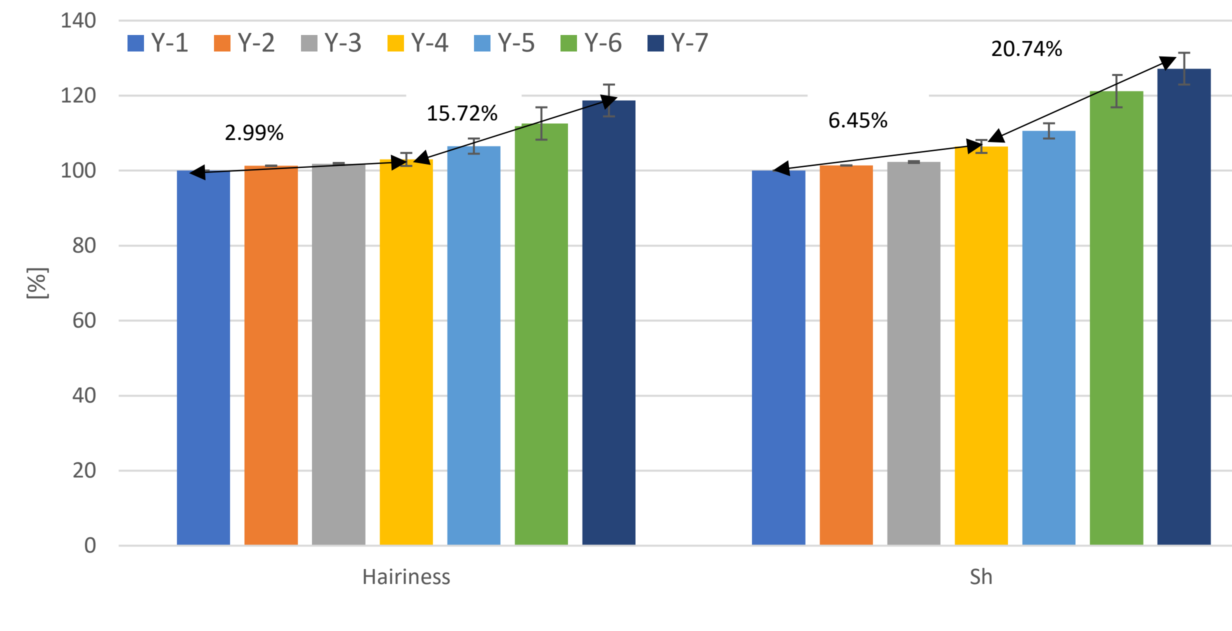


Y-1: (0% recycled cotton + 100% virgin cotton), Y-2: (17% recycled cotton + 83% virgin cotton), Y-3: (33% recycled cotton +67% virgin cotton), Y-4: (50% recycled cotton + 50% virgin cotton), Y-5: (67% recycled cotton +33% virgin cotton), Y-6: (83% recycled cotton + 17% virgin cotton), Y-7: (100% recycled cotton + 0% virgin cotton)

	Y-1	Y-2	Y-3	Y-4	Y-5	Y-6	Y-7
Unevenness (CVm%)	12.85	13.18	13.32	13.33	13.69	14.12	14.74
IPI/km	187.7	280.3	345.3	395.65	405.1	523.7	740
Neps (+200)/km	100.7	161.7	190.7	238.3	238.7	295.7	413.7
Thick place (+50)/km	46	61.3	71.3	73.3	75.7	92.7	119
Thin place (-40)/km	41	57.3	83.3	84.05	90.7	135.3	207.3

Figure 3. Imperfection and unevenness of yarn

The standard deviation of hairiness of yarn is also increased by 6.45% from 0% recycled cotton + 100% virgin cotton (Y-1) yarn to 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn and 20.74% from 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn to 100% recycled cotton + 0% virgin cotton (Y-7) yarn. The hairiness of yarns and their variation is increased continuously from Y-1 to Y-7 yarn because of having an increased amount of short fibre percentage.



Y-1: (0% recycled cotton + 100% virgin cotton), Y-2: (17% recycled cotton + 83% virgin cotton), Y-3: (33% recycled cotton +67% virgin cotton), Y-4: (50% recycled cotton + 50% virgin cotton), Y-5: (67% recycled cotton +33% virgin cotton), Y-6: (83% recycled cotton + 17% virgin cotton), Y-7: (100% recycled cotton + 0% virgin cotton)

	Y-1	Y-2	Y-3	Y-4	Y-5	Y-6	Y-7
Hairiness (H)	7.24	7.34	7.376	7.457	7.714	8.15	8.595
Sh	2.17	2.2	2.22	2.31	2.4	2.63	2.76

Figure 4. Yarn hairiness and its variations

Yarn strength

The RKM (Resistance per kilometre) test is normally applied to determine single yarn strength. B-work is a significant characteristic of yarn which is essential for several manufacturing stages of fabric. Figure 5 illustrates the strength and B-work values of several yarns (recycled) and it is visible that when recycled fibre% in yarn increases, the strength and B-work values gradually decrease. The reason is that recycled fibre contains a remarkable percentage of short fibre, and the length of fibre is relatively low as has been explained previously. During yarn production, the short fibres can't bind appropriately and migrate from the body of yarn and when a tensile force is applied to yarn the short fibre tends to slip instead of actively resisting this force, resulting in low strength. It is also noticed that the RKM of yarn is decreased by 24.02% from 0% recycled cotton + 100% virgin cotton (Y-1) yarn to 50% cotton (recycled) + 50% virgin cotton (Y-

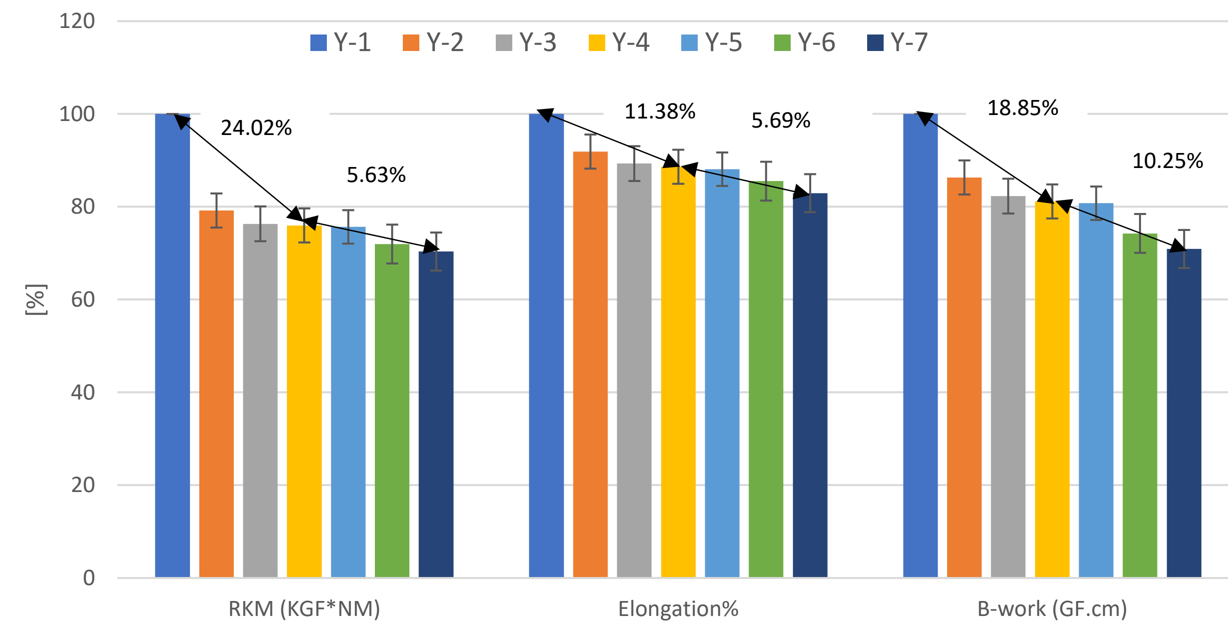
4) yarn and 5.63% from 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn to 100% recycled cotton + 0% virgin cotton (Y-7) yarn. The B-work of yarn is also decreased by 18.85% from 0% recycled cotton + 100% virgin cotton (Y-1) yarn to 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn and 10.25% from 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn to 100% recycled cotton + 0% virgin cotton (Y-7) yarn. The strength of yarn is decreased continuously from Y-1 to Y-7 yarn because of having an increased amount of short fibre percentage. It has been indicated in the previous work that the strength of yarn (Ne 8/1) is 10 cN/tex which was produced by rotor spinning utilizing 50% recycled cotton and 50% virgin cotton where blending of fibre was done in the blowroom stage [30]. In this study, the strength of yarn (Ne 8.25/1) is 12.71 cN/tex for 50% cotton (recycled) and 50% cotton (virgin) blend yarn. So, it is clear that when blending is done in 1st draw frame stage the strength (cN/tex) has been increased.

Elongation%

The yarn gets distributed within its constituent fibres when force is applied underscoring the significance of yarn elongation [5,36]. Yarn elongation is interrelated to the expansion of different fibres with the cohesion and alignment within the fibres in the construction of yarn [5,37]. Figure 5 indicates the elongation% of several yarns (recycled) and it is noticed that when recycled fibre% in yarn increases, the elongation gradually decreases. When force is applied, the short fibre present in fibre (recycled) cannot integrate properly within the structure of yarn which contributes to trouble-free detachment of fibre, resulting in lower elongation% of yarn. It is also seen that the yarn's elongation% is decreased by 11.38% from 0% recycled cotton + 100% virgin cotton (Y-1) yarn to 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn and 5.69% from 50% cotton (recycled) + 50% virgin cotton (Y-4) yarn to 100% recycled cotton + 0% virgin cotton (Y-7) yarn. The elongation of yarn is decreased continuously from Y-1 to Y-7 yarn because of having an increased amount of short fibre percentage. It has been indicated in the previous work that the elongation of yarn (Ne 8/1) is 7.4% which was produced by rotor spinning utilizing 50% recycled cotton and 50% virgin cotton where blending of fibre was done in the blowroom stage [30]. In this study, the elongation of yarn (Ne8.25/1) is 5.14% for 50% cotton (recycled) and 50% cotton (virgin) blend yarn. So, it is clear that when blending is done in 1st draw frame stage the elongation has been reduced.

Statistical analysis

Pearson correlation and significance of various portions of cotton fibre (recycled) with different specifications of recycled yarn are expressed in Table 9. Here, a negative correlation is noticed between recycled fibre percentage and yarn specifications including yarn RKM (Resistance per kilometre), B-work, and elongation%. It indicates that when recycled fibre% increases those yarn parameters decrease. On the other hand, a positive correlation has been noticed for recycled fibre percentages and yarn specifications such as yarn hairiness and its variation, unevenness%, IPI, thin place (-40), neps (+200), and thick place (+50)/km. It indicates that when recycled fibre% increases those yarn characteristics increase. All correlation values are noticed to be extremely significant because the 'P' value is less than 0.050.



Y-1: (0% recycled cotton + 100% virgin cotton), Y-2: (17% recycled cotton + 83% virgin cotton), Y-3: (33% recycled cotton +67% virgin cotton), Y-4: (50% recycled cotton + 50% virgin cotton), Y-5: (67% recycled cotton +33% virgin cotton), Y-6: (83% recycled cotton + 17% virgin cotton), Y-7: (100% recycled cotton + 0% virgin cotton)

	Y-1	Y-2	Y-3	Y-4	Y-5	Y-6	Y-7
RKM (KGF*NM)	16.73	13.25	12.77	12.71	12.66	12.04	11.77
Elongation%	5.8	5.33	5.18	5.14	5.11	4.96	4.81
B-work (GF.cm)	1614.8	1393.9	1329	1310.41	1304.1	1199.2	1144.9

Figure 5. Yarn strength and elongation%

Sustainable approach

In 2020 the international market size of denim fabric was $18.1 billion and is assumed to be $27.9 billion by 2030 [38]. As raw cotton costs account for more than 50 per cent of the manufacturing cost of yarn (ring) [39], the use of cotton (recycled) in producing yarn blending with 100% cotton will cause a significant decrease in basic materials cost. The cost of 100% cotton yarn is high compared to recycled cotton yarn and when the recycled cotton % is increased gradually in the blend the cost of yarns has been decreased proportionally. Total cotton production is 22%, or 24.7 million tons globally of the fibre market in 2021, while cotton (recycled) is only 0.27 million tons (1%) [1]. So, there is an opportunity to recycle cotton textiles. Production sectors all over the globe are effectively thinking about switching to sustainable production which brings various advantages such as decreasing costs related to raw materials and waste management [40]. For cultivating cotton 250 billion tons of water are required annually and to cultivate one kilogram of fibre (cotton) about 10,000 to 20,000 litres of water are necessary. In cotton fields using pesticides frequently is very harmful to the environment [5]. The manufacturing of recycled denim yarn in the article assists in decreasing the bad impact on the environment by cultivating virgin cotton [41]. It is visible that while utilizing recycled cotton the utilization of chemicals (pesticides) and water is too small for a traditional technique where only virgin cotton is used to manufacture yarn which is connected to the Sustainable Development Goals (SDG- 12), responsible consumption and production. The study utilized recycled cotton along with cotton (virgin) fibre instead of only 100% cotton (virgin) which is environment friendly. This novel approach utilizing fibres (recycled) will further minimize the requirement of cotton production and its proceedings, thereby giving remarkable offerings to environmental protection.

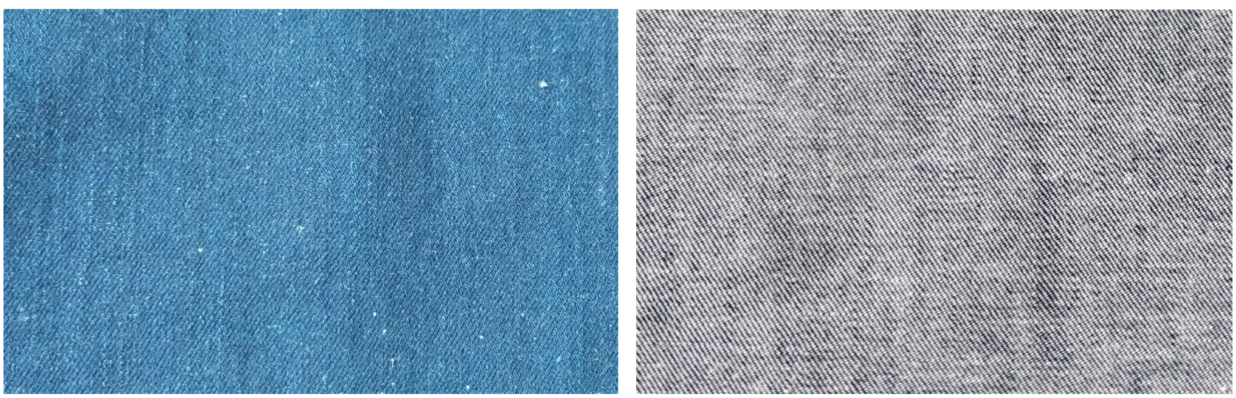
Table 9. Correlations (Pearson) for cotton (recycled)% with several characteristics of recycled cotton yarn

Parameter	Correlation coefficient	The sum of square and cross-products	Covariance	Sig.
Recycle cotton% and RKM (Resistance per kilometre) (KGF*NM)	-0.793994201	-126.75	-21.125	0.033
Recycle cotton% and B-work (GF.cm)	-0.912253528	-123.32	-20.15	0.004
Recycle cotton% and elongation %	-0.845160397	-41.260	-6.877	0.017
Recycle cotton% and hairiness (H)	0.903712136	122.430	20.405	0.005
Recycle cotton% and standard deviation of hairiness (sh)	0.947064094	129.32	21.52	0.004
Recycle cotton% and unevenness%	0.952668487	131.25	21.31	0.001
Recycle cotton% and IPI/km	0.947261933	124.31	20.19	0.001
Recycle cotton% and neps (+200%)/km	0.960232382	126.21	21.42	0.001
Recycle cotton% and thick place (+50%)/km	0.945980141	124.52	21.39	0.001
Recycle cotton% and thin place (-40%)/km	0.898647458	120.52	20.97	0.006

Fabric (denim) production

The manufactured yarns (rotor) have been inserted as weft to produce fabric (denim) in an air-jet weaving machine (Picanol Ommi Summum) to investigate the performances of yarns (Ne 8.25). As warp yarn, Ne 8.25 indigo dyed yarns (OE rotor) were utilized and the structure of fabric (denim) was 3/1 'Z' twill with EPIxPPI (40x36). In the weaving process, all yarns (Y-1 to Y-7) have been tried to process at 700 rpm and then increased to 750 rpm. It was noticed that in the weaving process the yarn (recycled), that contained less than 50% cotton (recycled), could run at 750 rpm, while yarns containing more than 50% recycled cotton could operate at the decreased speed of 700 rpm because more yarn breakage has been occurred at 750 rpm for yarns containing more than 50% recycled cotton. Yarns (recycled) containing more than 50% cotton (recycled) were suitable to insert as weft at a slightly decreased speed (700 rpm) in a weaving machine can be considered a remarkable achievement of the study.

The technical face and back side of the fabric produced by using recycled yarn (50% cotton (virgin) + 50% cotton (recycled) fibre) are shown in Figure 6. The appearance of the fabric is quite good. In the back (technical) side of the fabrics the weft yarn was prominent.



a) b)

Figure 6. The fabric is made from weft yarn (recycled) containing 50% cotton (virgin) + 50% cotton (recycled) fibre, a) technical face, b) technical backside

The colour of the technical back and face side of the fabric is different because indigo-dyed yarns were used as warp yarns, undyed yarns were used as weft yarns and the weft yarn was prominent in the backside.

However, the work does not investigate the characteristics of the fabric. To attain a real conclusion about the performance of yarn and fabric, it is essential to perform a comprehensive investigation of the fabric characteristics which will be done in the future study.

Cost analysis

The cost analysis of the developed yarn is shown in Table 10 where the first row indicates the 100% cotton (virgin) yarn cost denoted by 100: 0 (virgin cotton: recycled cotton). It is found that the cost of yarn (100% cotton) is $ 3.020 and with the increase of cotton (recycled)%, the yarn cost decreased. The cost of virgin cotton includes all costs, including transportation and packaging, and the recycled cotton's cost includes the pre-processing of cotton waste back into fibre. Here manufacturing overhead includes all costs required to produce yarn except raw materials cost and it also includes the entire recycling process and fibre-to-yarn production.

Table 10. Cost analysis of yarn

	The ratio of cotton (virgin) to cotton (recycled) in Yarn						
Cost elements	100:0	83:17	67:33	50:50	33:67	17:83	0:100
Recycled Cotton ($1.360 /kg), (A) [5]	0	0.15	0.29	0.44	0.66	0.79	1.01
Virgin cotton ($2.20/kg) (B) [5]	2.09	1.7	1.52	1.33	1.0	0.80	0
Total cost of raw materials, C=(A+B) (USD)	2.09	1.85	1.81	1.77	1.66	1.59	1.01
Manufacturing overhead, D (USD)	0.93	0.939	0.941	0.949	0.953	0.96	0.97
Total yarn cost (C+D) (USD)	3.020	2.789	2.751	2.719	2.613	2.550	1.980

CONCLUSION

The study explored the suitability and performance of producing denim yarn using recycled cotton fibre extracted from hard waste. The outcomes of the article focus on the significance of cotton (recycled) as a feasible substitute for traditional cotton production, addressing environmental issues. The statistical analysis provides significant relationships between recycled cotton proportion and yarn characteristics such as a negative correlation is noticed between yarn characteristics and recycled fibre% including yarn's RKM (Resistance per kilometre), B-work, and elongation% but a positive correlation has been noticed between yarn characteristics and recycled fibre% such as hairiness and its variation, IPI, unevenness, thin place (-40%), neps (+200%), and thick place (+50%)/km. The CVm%, IPI, and hairiness of yarn and its variation are increased by several percentages from 0% recycled cotton + 100% virgin cotton yarn to 50% cotton (recycled) + 50% virgin cotton yarn and also from 50% cotton (recycled)+ 50% virgin cotton yarn to 100% recycled cotton + 0% virgin cotton yarn but the strength and elongation% are decreased by several percentages from 0% recycled cotton + 100% virgin cotton yarn to 50% cotton (recycled) + 50% virgin cotton yarn and also from 50% cotton (recycled) + 50% virgin cotton yarn to 100% recycled cotton + 0% virgin cotton yarn. Yarns (recycled) containing more than 50% cotton (recycled) were suitable to insert as weft in a weaving machine to produce fabric (denim).

The study focuses on minimizing the environmental impacts of denim production by integrating sustainable recycled cotton. The natural resources savings associated with cotton cultivation align with Sustainable Development Goals, contributing to SDG-12 (Responsible Consumption and Production). The study emphasized the environmental impact of incorporating recycled cotton to manufacture yarn contributing to a sustainable approach.

Author Contributions

Conceptualization – Habib A, Cozeli N, Kanat H, Babaarslan O; methodology – Cozeli N, Kanat H, Babaarslan O; formal analysis – Cozeli N, Kanat H, Tan S, Babaarslan O; investigation – Habib A, Babaarslan O; resources – Habib A, Cozeli N, Kanat H, Babaarslan O; writing-original draft preparation – Habib A, Cozeli N, Kanat H, Tan S; writing-review and editing – Babaarslan O; visualization – Habib A and Tan S; supervision – Babaarslan O. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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REFERENCES

[1] Textile Exchange. Preferred fibre & materials market report. Textile Exchange; 2022. Available from: https://text ileexchange.org/app/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf.

[2] McLoughlin J, Hayes S, Paul R. Cotton fibre for denim manufacture. In: Paul R, editor. Denim Manufacture, Finishing, and Applications. UK: Woodhead Publishing; 2015. p. 15-36. https://doi.org/10.1016/B978-0-85709-843-6.00002-0

[3] Gupta R, Kushwaha A, Dave D, Mahanta NR. Waste management in fashion and textile industry: Recent advances and trends, life-cycle assessment, and circular economy. In: Hussain CM et al., editors. Emerging Trends to Approaching Zero Waste: Environmental and Social Perspectives. 2022. p. 215-242. https://doi.org/10.1016/B978-0-323-85403-0.00004-9

[4] Niinimäki K, Karell E. Closing the Loop: Intentional Fashion Design Defined by Recycling Technologies. In: Vignali G, Reid LF, Ryding D, Henninger CE, editors. Technology-Driven Sustainability. Cham: Palgrave Macmillan; 2020. p. 7-25. https://doi.org/10.1007/978-3-030-15483-7_2

[5] Uddin AJ, Rahman M. Sustainable and cleaner production of elastic core-spun yarns for stretch denim with maximal utilization of recycled cotton extracted from pre-consumer fabric waste. Heliyon. 2024; 10(4):e25444. https://doi.org/10.1016/j.heliyon.2024.e25444

[6] De Ponte C, Liscio MC, Sospiro P. State of the art on the Nexus between sustainability, the fashion industry, and sustainable business model. Sustainable Chemistry and Pharmacy. 2023; 32(1):100968. https://doi.org/10.1016/j.scp.2023.100968

[7] Garcia-Ortega B, Galan-Cubillo J, Llorens-Montes FJ, De-Miguel-Molina B. Sufficient consumption as a missing link toward sustainability: The case of fast fashion. Journal of Cleaner Production. 2023; 399(1):136678. https://doi.org/10.1016/j.jclepro.2023.136678

[8] Reza MM, Begum HA, Uddin AJ. Potentiality of sustainable corn starch-based biocomposites reinforced with cotton filter waste of spinning mill. Heliyon. 2023; 9(5):15697. https://doi.org/10.1016/j.heliyon.2023.e15697

[9] Koszewska M. Circular economy—Challenges for the textile and clothing industry. Autex Research Journal. 2018; 18(4):337-347. https://doi.org/10.1515/aut-2018-0023

[10] Vadicherla T, Saravanan D, Muthu Ram M, Suganya K. Fashion Renovation via Upcycling. In: Muthu S, editor. Textiles and Clothing Sustainability: Recycled and upcycled textiles and fashion. Singapore: Springer; 2017. p. 1-54. https://doi.org/10.1007/978-981-10-2146-6_1

[11] Periyasamy AP, Militky J. Sustainability in Textile Dyeing: Recent Developments. In: Muthu S, Gardetti M, editors. Sustainability in the Textile and Apparel Industries: Production Process Sustainability. Cham: Springer; 2020. p. 37-79. https://doi.org/10.1007/978-3-030-38545-3_2

[12] Turnbull J, Stevens K, Mzikian P, Bertele M, Cavadini F, Crippa M, et al. Achieving a Circular Textiles Economy Facilitated by Innovative Technology. In: Matthes A, Beyer K, Cebulla H, Arnold MG, Schumann A, editors. Sustainable Textile and Fashion Value Chains. Cham: Springer; 2020. p. 205-236. https://doi.org/10.1007/978-3-030-22018-1_12

[13] Domina T, Koch K. The textile waste lifecycle. Clothing and Textiles Research Journal. 1997; 15(2):96-102. https://doi.org/10.1177/0887302X9701500204

[14] Hawley JM. Digging for diamonds: A conceptual framework for understanding reclaimed textile products. Clothing and Textiles Research Journal. 2006; 24(3):262-275. https://doi.org/10.1177/0887302X06294626

[15] Franco MA. Circular economy at the micro level: A dynamic view of incumbents' struggles and challenges in the textile industry. Journal of Cleaner Production. 2017; 168:833-845. https://doi.org/10.1016/j.jclepro.2017.09.056

[16] Uddin MB, Uddin AJ. A sustainable approach to manufacture mélange yarn from waste jute fibre and pre-consumer cotton fabric waste using an I-optimal mixture design. Journal of Cleaner Production. 2023; 421:138376. https://doi.org/10.1016/j.jclepro.2023.138376

[17] Utebay B, Celik P, Cay A. Valorization of fabric wastes through the production of recycled cotton yarns by compact ring and open-end rotor spinning. Journal of Cleaner Production. 2023; 409:137135. https://doi.org/10.1016/j.jclepro.2023.137135

[18] Okandan H, Yildirim N, Kertmen M, Türksoy H. The Effects of OE-Rotor Spinning Parameters on Yarn Properties Produced from Recycled/Virgin Cotton Fibres Blend. Uluslararası Bilim Teknoloji ve Tasarım Dergisi. 2023; 4(1):1-15.

[19] Ute TB, Celik P, Uzumcu MB. Utilization of cotton spinning mill wastes in yarn production. In: Korlu A, editor. Textile industry and environment. UK: Intechopen; 2019. p. 53-66. http://dx.doi.org/10.5772/intechopen.85127

[20] Awgichew D, Sakthivel S, Solomon E, Bayu A, Legese R, Asfaw D, et al. Experimental study and effect on recycled fibres blended with rotor/OE yarns for the production of handloom fabrics and their properties. Advances in Materials Science and Engineering. 2021: 4334632. https://doi.org/10.1155/2021/4334632

[21] Islam MI, Patwary MI, Ali SB, Reza MM, Islam MM, Hossain MT, et al. Comparative analysis of recycled rotor yarns made from cutting table waste that contains larger and regular percentages of recycled cotton. Cellulose. 2023: 31:677-684. https://doi.org/10.1007/s10570-023-05654-2

[22] Arafat Y, Uddin AJ. Recycled fibres from pre-and post-consumer textile waste as blend constituents in manufacturing 100% cotton yarns in ring spinning: A sustainable and eco-friendly approach. Heliyon. 2022; 8(11):11275. https://doi.org/10.1016/J.HELIYON.2022.E11275

[23] Telli A, Babaarslan O. Usage of recycled cotton and polyester fibres for sustainable staple yarn technology. Textile and Apparel. 2017; 27(3):224-233.

[24] Yilmaz D, Yelkovan S, Tirak Y. Comparison of the effects of different cotton fibre wastes on different yarn types. Fibres & Textiles in Eastern Europe. 2017; 4(124):19-30.

[25] Şentürk ÇD, Üte TB. A Research on Properties of Knitted Fabrics Produced with Ring and Rotor-Spun Yarns Containing Recycled Cotton Fibre. In: Kumbasar, EPA, editor. IITAS 2023. XVIth International Izmir Textile & Apparel Symposium; 25-27 October 2023; Izmir; 2023. p 140.

[26] Yuksekkaya ME, Celep G, Dogan G, Tercan M, Urhan B. A comparative study of physical properties of yarns and fabrics produced from virgin and recycled fibres. Journal of Engineered Fibres and Fabrics. 2016; 11(2):68-76. https://doi.org/10.1177/155892501601100209

[27] Duru PN, Babaarslan O. Determining an optimum opening roller speed for spinning polyester/waste blend rotor yarns. Textile Research Journal. 2003; 73(10):907-911. https://doi.org/10.1177/004051750307301010

[28] Khan MKR, Hossain MM, Sarker RC. Statistical Analysis and Predicting the Properties of Cotton/Waste Blending Open-end Rotor Yarn Using Taguchi OA Design. International Journal of Textile Science. 2015; 4(2):27-35. https://doi.org/10.5923/j.textile.20150402.01

[29] Telli A, Babaarslan O. Commercialized denim fabric production with post-industrial and post-consumer wastes. Textile and Apparel. 2016; 26(2):213-220.

[30] Arafa HM. Producing Yarns from Blends of Card Waste, Recycled Fabric, and Medium Quality Cotton. Egyptian Journal of Agricultural Sciences. 2019; 70(4):453-460.

[31] Halimi MT, Hassen MB, Azzouz B, Sakli F. Effect of cotton waste and spinning parameters on rotor yarn quality. Journal of the Textile Institute. 2007; 98(5):437-442. https://doi.org/10.1080/00405000701547649

[32] Uddin AJ, Roy P. Transforming melange fabric waste into melange yarn employing compact, Siro, and compact-Siro spinning: A cleaner and sustainable strategy. Cleaner Waste Systems. 2024; 8:100142. https://doi.org/10.1016/j.clwas.2024.100142

[33] Türksoy HG, Kılıç G, Üstüntağ S, Yılmaz D. A comparative study on properties of dual-core yarns. The Journal of the Textile Institute. 2019; 110(7):980-988. https://doi.org/10.1080/00405000.2018.1534541

[34] Deng Z, Yu L, Wang L, Ke W. An algorithm for cross-fibre separation in yarn hairiness image processing. The Visual Computer. 2023; 40:3591-3599. https://doi.org/10.1007/s00371-023-03053-z

[35] Thilagavathi G, Karthik T. Process control and yarn quality in spinning. CRC Press. 2016. 400 p.

[36] Habib A, Olgun Y, Babaarslan O. Development of Dual-Core Spun Yarn Using Different Filaments as a Core and its Impact on Denim Fabric Properties. Textile & Leather Review. 2024; 7:534-549. https://doi.org/10.31881/TLR.2024.024

[37] Islam MI, Uddin AJ. Enhancing the quality of elastane-cotton core yarn by compact spinning. Heliyon. 2022; 8(6):09562. https://doi.org/10.1016/j.heliyon.2022.e09562

[38] Allied Market Research. Denim Fabric Market Research-2030. Allied Market Research; 2021. Available from: https://www.alliedmarketresearch.com/press-release/denim-fabric-market.html

[39] Oner E, Topcuoglu S, Kutlu O. The effect of cotton fibre characteristics on yarn properties. Materials Science and Engineering. 2019; 459:012057. https://doi.org/10.1088/1757-899X/459/1/012057

[40] Mungai E and Ndiritu SW. Peeling the Onion! What are the drivers and barriers of cleaner production? A case of the Kenyan manufacturing SMEs. Journal of Cleaner Production. 2023; 383:135436. https://doi.org/10.1016/j.jclepro.2022.135436

[41] Habib A, Mamun MA, BABAARSLAN O. Development of Sustainable Dual core-spun Yarns Using Several Filaments and Recycled Cotton Sourced from Pre-consumer Fabric Waste. Heliyon. 2024; 10:29392. https://doi.org/10.1016/j.heliyon.2024.e29392